Chapter 6
Magnetic Methods

6-1. Introduction

a. The earth possesses a magnetic field caused primarily by sources in the core. The form of the field is roughly the same as would be caused by a dipole or bar magnet located near the earth's center and aligned subparallel to the geographic axis. The intensity of the earth's field is customarily expressed in S.I. units as nanoteslas (nT) or in an older unit, gamma (γ): 1 γ = 1 nT = 10^{-3} µT. Except for local perturbations, the intensity of the earth's field varies between about 25 and 80 µT over the coterminous United States.

b. Many rocks and minerals are weakly magnetic or are magnetized by induction in the earth's field, and cause spatial perturbations or "anomalies" in the earth's main field. Man-made objects containing iron or steel are often highly magnetized and locally can cause large anomalies up to several thousands of nT. Magnetic methods are generally used to map the location and size of ferrous objects. Determination of the applicability of the magnetics method should be done by an experienced engineering geophysicist. Modeling and incorporation of auxiliary information may be necessary to produce an adequate work plan.

6-2. Theory

The earth's magnetic field dominates most measurements on the surface of the earth. The earth's total field intensity varies considerably by location over the surface of the earth. Most materials except for permanent magnets, exhibit an induced magnetic field due to the behavior of the material when the material is in a strong field such as the earth's. Induced magnetization (sometimes called magnetic polarization) refers to the action of the field on the material wherein the ambient field is enhanced causing the material itself to act as a magnet. The field caused by such a material is directly proportional to the intensity of the ambient field and to the ability of the material to enhance the local field, a property called magnetic susceptibility. The induced magnetization is equal to the product of the volume magnetic susceptibility and the inducing field of the earth:

$$I = k\,F \tag{6-1}$$

where

k = volume magnetic susceptibility (unitless)

I = induced magnetization per unit volume

F = field intensity in tesla (T)

a. For most materials k is much less than 1 and, in fact, is usually of the order of 10^{-6} for most rock materials. The most important exception is magnetite whose susceptibility is about 0.3. From a geologic standpoint, magnetite and its distribution determine the magnetic properties of most rocks. There are other important magnetic minerals in mining prospecting, but the amount and form of magnetite within a rock determines how most rocks respond to an inducing field. Iron, steel, and other ferromagnetic alloys have susceptibilities one to several orders of magnitude larger than magnetite. The exception is stainless steel, which has a small susceptibility.

b. The importance of magnetite cannot be exaggerated. Some tests on rock materials have shown that a rock containing 1 percent magnetite may have a susceptibility as large as 10^{-3}, or 1,000 times larger than most rock materials. Table 6-1 provides some typical values for rock materials. Note that the range of values given for each sample generally depends on the amount of magnetite in the rock.

Table 6-1
Approximate Magnetic Susceptibility of Representative Rock Types

Rock Type	Susceptibility (*k*)
Altered ultra basics	10^{-4} to 10^{-2}
Basalt	10^{-4} to 10^{-3}
Gabbro	10^{-4}
Granite	10^{-5} to 10^{-3}
Andesite	10^{-4}
Rhyolite	10^{-5} to 10^{-4}
Metamorphic rocks	10^{-4} to 10^{-6}
Most sedimentary rocks	10^{-6} to 10^{-5}
Limestone and chert	10^{-6}
Shale	10^{-5} to 10^{-4}

c. Thus it can be seen that in most engineering and environmental scale investigations, the sedimentary and alluvial sections will not show sufficient contrast such that magnetic measurements will be of use in mapping the geology. However, the presence of ferrous materials in ordinary municipal trash and in most industrial waste does allow the magnetometer to be effective in direct detection of landfills. Other ferrous objects which may be detected include pipelines, underground storage tanks, and some ordnance.

6-3. Field Work

Ground magnetic measurements are usually made with portable instruments at regular intervals along more or less straight and parallel lines which cover the survey area. Often the interval between measurement locations (stations) along the lines is less than the spacing between lines.

a. The magnetometer is a sensitive instrument which is used to map spatial variations in the earth's magnetic field. In the proton magnetometer, a magnetic field which is not parallel to the earth's field is applied to a fluid rich in protons causing them to partly align with this artificial field. When the controlled field is removed, the protons precess toward realignment with the earth's field at a frequency which depends on the intensity of the earth's field. By measuring this precession frequency, the total intensity of the field can be determined. The physical basis for several other magnetometers, such as the cesium or rubidium-vapor magnetometers, is similarly founded in a fundamental physical constant. The optically pumped magnetometers have increased sensitivity and shorter cycle times (as small as 0.04 s) making them particularly useful in airborne applications.

(1) The incorporation of computers and non-volatile memory in magnetometers has greatly increased the ease of use and data handling capability of magnetometers. The instruments typically will keep track of position, prompt for inputs, and internally store the data for an entire day of work. Downloading the information to a personal computer is straightforward and plots of the day's work can be prepared each night.

(2) To make accurate anomaly maps, temporal changes in the earth's field during the period of the survey must be considered. Normal changes during a day, sometimes called diurnal drift, are a few tens of nT but changes of hundreds or thousands of nT may occur over a few hours during magnetic storms. During severe magnetic storms, which occur infrequently, magnetic surveys should not be made. The correction for diurnal drift can be made by repeat measurements of a base station at frequent intervals. The measurements at field stations are then corrected for temporal variations by assuming a linear change of the field between repeat base station readings. Continuously recording magnetometers can also be used at fixed base sites to monitor the temporal changes. If time is accurately recorded at both base site and field location, the field data can be corrected by subtraction of the variations at the base site.

(3) The base-station memory magnetometer, when used, is set up every day prior to collection of the magnetic data. The base station ideally is placed at least 100 m from any large metal objects or travelled roads and at least 500 m from any power lines when feasible. The base station location must be very well described in the field book as others may have to locate it based on the written description.

(4) Some QC/QA procedures require that several field-type stations be occupied at the start and end of each day's work. This procedure indicates that the instrument is operating consistently. Where it is important to be able to reproduce the actual measurements on a site exactly (such as in certain forensic matters) an additional procedure is required. The value of the magnetic field at the base station must be asserted (usually a value close to its reading on the first day) and each day's data corrected for the difference between the asserted value and the base value read at the beginning of the day. As the base may vary by 10-25 nT or more from day to day, this correction ensures that another person using the SAME base station and the SAME asserted value will get the same readings at a field point to within the accuracy of the instrument. This procedure is always good technique but is often neglected by persons interested in only very large anomalies (> 500 nT, etc.).

b. Intense fields from man-made electromagnetic sources can be a problem in magnetic surveys. Most magnetometers are designed to operate in fairly intense 60-Hz and radio frequency fields. However extremely low frequency fields caused by equipment using direct current or the switching of large alternating currents can be a problem. Pipelines carrying direct current for cathodic protection can be particularly troublesome. Although some modern ground magnetometers have a sensitivity of 0.1 nT, sources of cultural and geologic noise usually prevent full use of this sensitivity in ground measurements.

(1) After all corrections have been made, magnetic survey data are usually displayed as individual profiles or as contour maps. Identification of anomalies caused by cultural features, such as railroads, pipelines, and bridges is commonly made using field observations and maps showing such features.

(2) For some purposes a close approximation of the gradient of the field is determined by measuring the difference in the total field between two closely spaced

sensors. The quantity measured most commonly is the vertical gradient of the total field.

(3) The magnetometer is operated by a single person. However, grid layout, surveying, or the buddy system may require the use of another technician. If two magnetometers are available production is usually doubled as the ordinary operation of the instrument itself is straightforward.

c. Distortion.

(1) Steel and other ferrous metals in the vicinity of a magnetometer can distort the data. Large belt buckles, etc., must be removed when operating the unit. A compass should be more than 3 m away from the magnetometer when measuring the field. A final test is to immobilize the magnetometer and take readings while the operator moves around the sensor. If the readings do not change by more than 1 or 2 nT, the operator is "magnetically clean." Zippers, watches, eyeglass frames, boot Grommets, room keys, and mechanical pencils, can all contain steel or iron. On very precise surveys, the operator effect must be held under 1 nT.

(2) To obtain a representative reading, the sensor should be operated well above the ground. This procedure is done because of the probability of collections of soil magnetite disturbing the reading near the ground. In rocky terrain where the rocks have some percentage of magnetite, sensor heights of up to 4 m have been used to remove near-surface effects. One obvious exception to this is some types of ordnance detection where the objective is to detect near-surface objects. Often a rapid-reading magnetometer is used (cycle time less than 1/4 s) and the magnetometer is used to sweep across an area near the ground. Small ferrous objects can be detected, and spurious collections of soil magnetite can be recognized by their lower amplitude and dispersion. Ordnance detection requires not only training in the recognition of dangerous objects, but experience in separating small, intense, and interesting anomalies from more dispersed geologic noise.

d. Data recording methods will vary with the purpose of the survey and the amount of noise present. Methods include: taking three readings and averaging the results, taking three readings within a meter of the station and either recording each or recording the average. Some magnetometers can apply either of these methods and even do the averaging internally. An experienced field geophysicist will specify which technique is required for a given survey. In either case, the time of the reading is also recorded unless the magnetometer stores the readings and times internally.

(1) Sheet-metal barns, power lines, and other potentially magnetic objects will occasionally be encountered during a magnetic survey. When taking a magnetic reading in the vicinity of such items, describe the interfering object and note the distance from it to the magnetic station in your field book.

(2) Items to be recorded in the field book for magnetics:

(a) Station location, including locations of lines with respect to permanent landmarks or surveyed points.

(b) Magnetic field and/or gradient reading.[1]

(c) Time.[1]

(d) Nearby sources of potential interference.

(3) The experienced magnetics operator will be alert for the possible occurrence of the following conditions:

(a) Excessive gradients may be beyond the magnetometer's ability to make a stable measurement. Modern magnetometers give a quality factor for the reading. Multiple measurements at a station, minor adjustments of the station location and other adjustments of technique may be necessary to produce repeatable, representative data.

(b) Nearby metal objects may cause interference. Some items, such as automobiles, are obvious, but some subtle interference will be recognized only by the imaginative and observant magnetics operator. Old buried curbs and foundations, buried cans and bottles, power lines, fences, and other hidden factors can greatly affect magnetic readings.

e. Interpretation. Total magnetic disturbances or anomalies are highly variable in shape and amplitude; they are almost always asymmetrical, sometimes appear complex even from simple sources, and usually portray the combined effects of several sources. An infinite number of possible sources can produce a given anomaly, giving rise to the term ambiguity.

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[1] Optional depending on use of memory magnetometers which record these parameters and the station number.

(1) One confusing issue is the fact that most magnetometers used measure the total field of the earth: no oriented system is recorded for the total field amplitude. The consequence of this fact is that only the component of an anomalous field in the direction of earth's main field is measured. Figure 6-1 illustrates this consequence of the measurement system. Anomalous fields that are nearly perpendicular to the earth's field are undetectable.

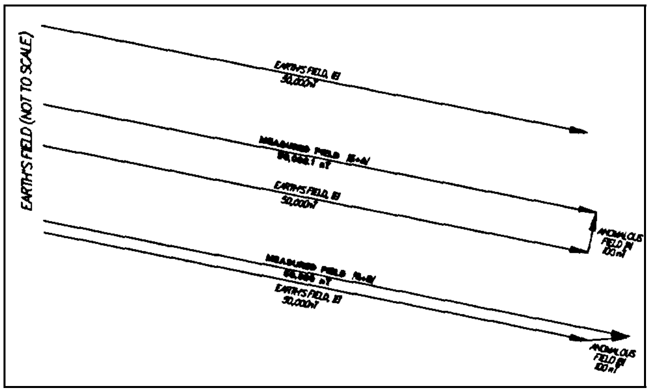

Figure 6-1. Magnetic field vector examples for two anomalous targets

(2) Additionally, the induced nature of the measured field makes even large bodies act as dipoles; that is, like a large bar magnet. If the (usual) dipolar nature of the anomalous field is combined with the measurement system that measures only the component in the direction of the earth's field, the confusing nature of most magnetic interpretations can be appreciated.

(3) To achieve a qualitative understanding of what is occurring, consider Figure 6-2. Within the contiguous United States, the magnetic inclination, that is the angle the main field makes with the surface, varies from 55-70 deg. The figure illustrates the field associated with the main field, the anomalous field induced in a narrow body oriented parallel to that field, and the combined field that will be measured by the total-field magnetometer. The scalar values which would be measured on the surface above the body are listed. From this figure, one can see how the total-field magnetometer records only the components of the anomalous field.

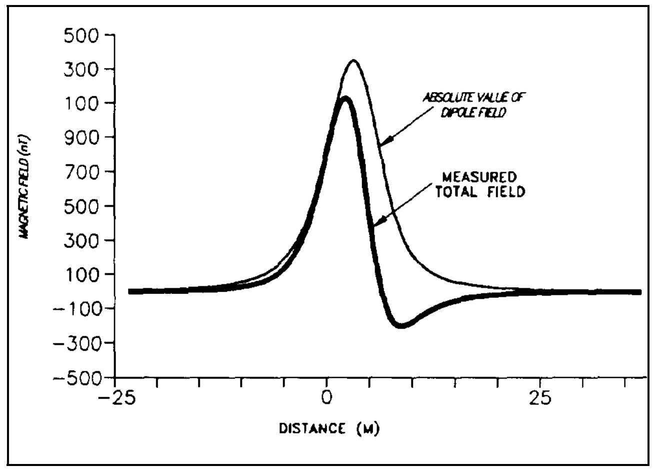

Figure 6-2. Actual and measured fields due to magnetic inclination